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Technical Report

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EFFECT OF AGGREGATE SIZE ON
THERMAL SHOCK RESISTANCE

6 November 1961

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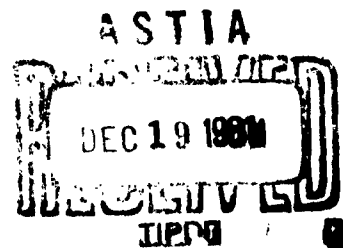


U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

62-1-5

XEROX



EFFECT OF AGGREGATE SIZE ON THERMAL SHOCK RESISTANCE

Y-F015-15-106

Type C Final Report

by

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OBJECT OF TASK

To determine if the size of the aggregate used in a concrete mix is a contributing factor to the explosive spalling that takes place when concrete pavement surfaces are subjected to thermal shock.

ABSTRACT

In connection with the effect of turbojet engine exhaust on concrete pavements, NCEL conducted two studies, one on the effect of thermal shock on concrete aggregates and one on the effect of temperature rise on cement paste. The aggregate study is reported herein; a summary of the cement-paste study is given in an appendix.

In this aggregate study, five sizes of five different aggregates in oven-dried and saturated-surface-dried conditions were subjected to eleven degrees of furnace temperatures between 1000 and 2000 F. Three samples were tested for each combination, making a total of 1650 tests in all. Breakdown of the aggregates was established by comparing the before-heating and after-heating sieve analyses.

It was found that heating caused breakdown of the aggregates. By statistical analysis, it was determined that the larger aggregates had more breakdown than the smaller ones, and that the higher temperatures caused more breakdown than the lower temperatures. It was also determined that the saturated-surface-dried aggregates experienced more breakdown than the oven-dried aggregates.

It appears from this investigation that smaller aggregates are preferable to larger aggregates for heat-resistant concrete. On the basis of both the aggregate and cement-paste studies, it appears preferable to have the aggregates and the cement paste as dry as possible before the concrete is subjected to high thermal shock conditions.

A recommendation is given to conduct an investigation to determine the refractoriness of concrete slabs under field conditions.

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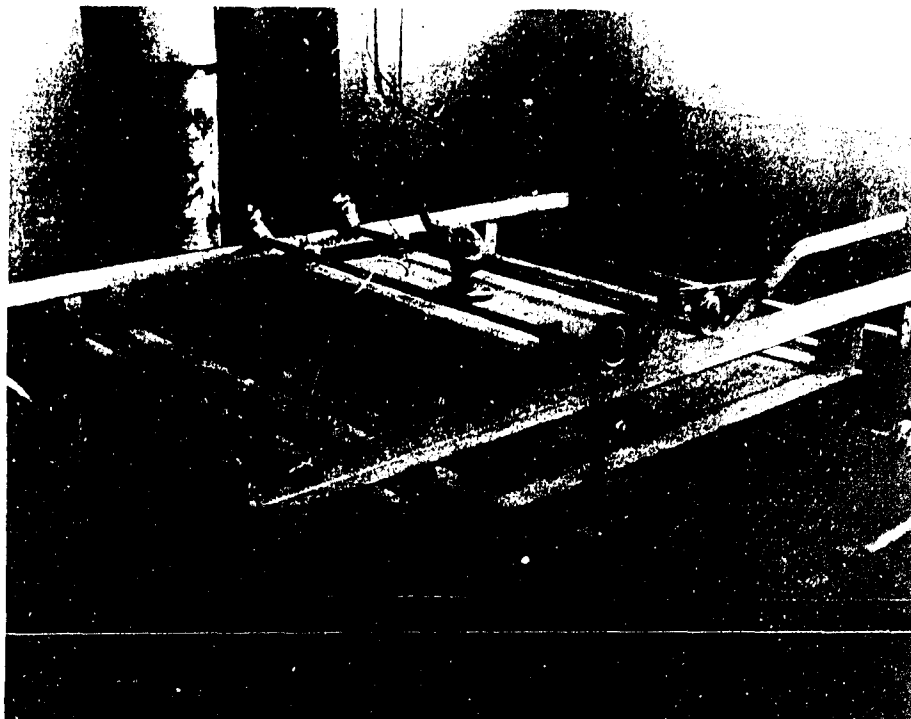


Figure 1. Gas-fired furnace.

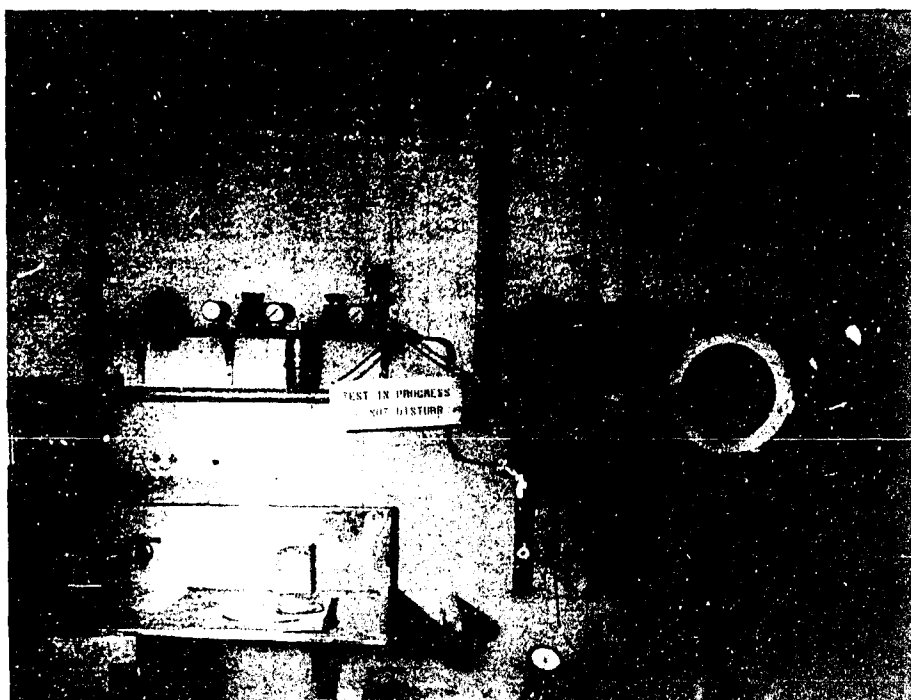


Figure 2. Circular-chart pneumatic program controller.

As the cam rotated, the cam follower moved the set-point indicator. The indicator in turn changed the controlled pressure of the pneumatic control unit connected to the diaphragm valve. Thus the volume of air-gas mixture was regulated to obtain the furnace temperature indicated on the cam at any time. Likewise, when the cam was stopped at a certain index, the temperature was maintained at the indicated level.

With the pneumatic program controller, it was possible to raise the furnace temperature from about 200 to 2000 F at constant rates of approximately 8 to 14 F per second. It was also possible to maintain any temperature between approximately 1000 to 2000 F. It appeared that the furnace with the controller was capable of producing temperatures equivalent to those on pavement surfaces being subjected to turbojet engine exhausts. However, there were no impinging gas velocities approaching those of jet engine exhausts.

AGGREGATES FOR TEST

Five aggregates were arbitrarily selected for this investigation. These were Santa Clara River gravel, San Gabriel River gravel, crushed Virginia diabase, a blast-furnace slag, and Haydite.

The Santa Clara and San Gabriel gravels, which were excavated from river beds in California, were composed of rocks which had varied minerals and textures. Granites mostly with ferrous grains, oil shales, cherts, mudstones, sandstones and others were identified in these gravels. It appeared that the San Gabriel gravel contained more granites and less mudstones and sandstones than the Santa Clara gravel.

The crushed Virginia diabase was from deposits in Centerville, Virginia. The National Bureau of Standards reported* that grains of feldspar and hornblende were apparent in this rock, and that it had a low porosity and was practically quartz-free. Some of the rocks were round and brownish and appeared to be weathered, but most were crushed, gray pieces with a uniform texture.

The slag, obtained from a California steel mill, consisted of gray pieces with surface voids. A portion of the slag had more voids and appeared to have a rougher texture than the rest.

The Haydite was a crushed expanded shale, a lightweight aggregate generally used with high aluminous cements to make thermal-insulating concretes. Like the blast-furnace slag, surface voids in the Haydite were apparent.

Figure 3 shows samples of the various aggregates, and Table I gives the significant physical properties of each.

* National Bureau of Standards Quarterly Report on Evaluation of Refractory Qualities of Concretes for Jet Aircraft Warm-up, Power Check, Maintenance Aprons, and Runways, by W. L. Pendergast, et al. Washington, D. C., 5 October 1956 (Report No. 4869).

INTRODUCTION

The operation of modern Navy turbojet aircraft subjects airfield pavements to some severe conditions. To accommodate these aircraft safely and efficiently, airfield pavements must be able to carry heavy wheel loads with high tire pressures, possess good skid resistance, and have enough refractory qualities to resist the high-temperature and high-velocity exhaust gases of jet engines. The pavements must also resist the effects of jet fuel spillage and be free from loose fragments of aggregate or other materials that might be drawn into the jet intake and cause serious damage to the engine.

These requirements have necessitated continued research to find improved pavement materials. In studies of the effect of jet engine exhaust on pavement, NCEL evaluated a number of portland cement concrete pavements. Damage in the form of spalling of some concrete pavement surfaces was observed during exposure to afterburner power. In an effort to determine the cause or causes of the damage, two separate investigations were conducted, one on concrete aggregates and one on cement paste. The investigation of the effect of thermal shock on concrete aggregates is reported herein; a summary of the cement paste study is given in Appendix A.

In the aggregate investigation, the plan was to subject various sizes of different aggregates in the oven-dried and saturated-surface-dried conditions to high temperatures to determine the amount of breakdown caused by thermal shock. A correlation was anticipated between the amount of breakdown and the size of aggregate.

TEST EQUIPMENT

A gas-fired brick furnace with an opening on top, shown in Figure 1, was used to expose the aggregates to thermal shock. The size of the furnace chamber was 10 inches by 18-1/2 inches by 11 inches deep.

A blower with an output of 150 cfm supplied air through a diaphragm valve to two adjustable proportional air-gas mixers. The mixture was in turn conveyed to two burner nozzles located near diagonally opposite corners of the furnace chamber. The exhaust gas was expelled through a smokestack connected to a port located in the base of the furnace chamber.

A circular-chart pneumatic program controller with a chromel-alumel thermocouple protruding approximately 1/2 inch below the furnace lid was used to control the furnace temperature. This instrument, shown in Figure 2, consisted of motor-driven cams cut to various time-temperature profiles, a cam follower connected by a cable to a set-point indicator, a pneumatic control unit and a primary element.

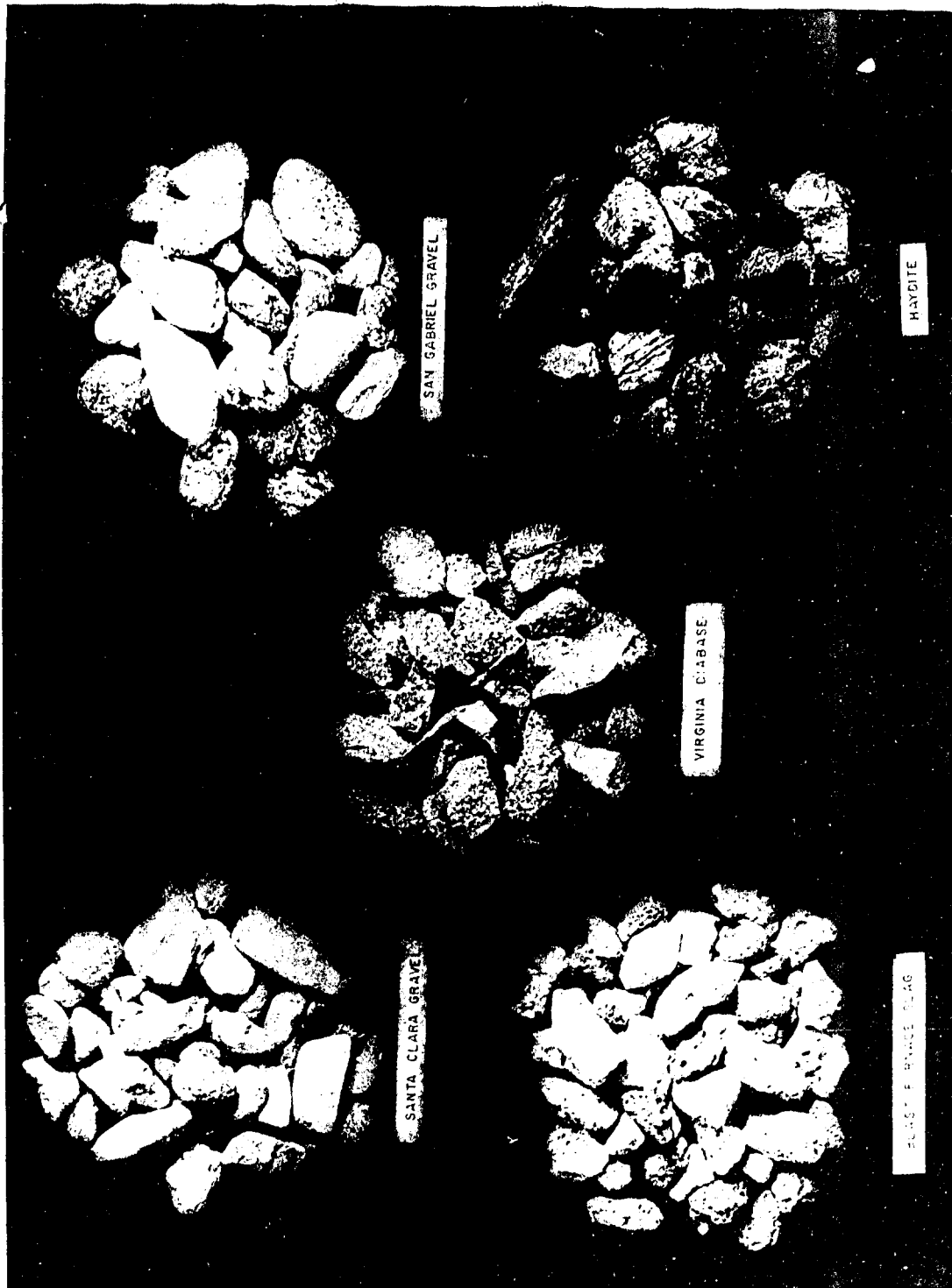


Figure 3. Samples of aggregates.

Table 1. Physical Properties of Aggregates

Aggregate	24-Hour Absorption (percent)	Bulk Specific Gravity	Los Angeles Abrasion (percent loss)
Santa Clara Gravel	3.1	2.53	28
San Gabriel Gravel	1.6	2.66	33
Virginia Diabase	0.6	2.96	26
Blast-Furnace Slag	3.1	2.43	34
Haydite	6.7	1.24	47

METHOD OF TEST

Samples

Sufficient quantities of an aggregate were washed, dried in an oven to constant weight, and segregated into the following sizes by screening in standard mechanical sieves:

1. 1-inch (passing 1-1/2-inch and retained on 1-inch)
2. 3/4-inch (passing 1-inch and retained on 3/4-inch)
3. 1/2-inch (passing 3/4-inch and retained on 1/2-inch)
4. 3/8-inch (passing 1/2-inch and retained on 3/8-inch)
5. No. 4 (passing 3/8-inch and retained on No. 4)

The fine fraction of the aggregates was not under consideration.

Three oven-dried and three saturated-surface-dried samples were made for each aggregate type and size and test temperature. Each sample, which consisted of enough oven-dried aggregate to cover the bottom of a furnace pan (approximately 10 inches by 13 inches) with one layer, was weighed. Then the saturated-surface-dried samples were made by soaking the required number of oven-dried samples in water for 24 hours and removing the free water from the surfaces with a dry towel.

Heating

The samples were then subjected to various levels of thermal shock in a furnace to compare the breakdown of the various types and sizes of aggregates in the two conditions of drying. The furnace was brought to a test temperature and the furnace pan containing a sample at room temperature was placed in the furnace and heated for three minutes with the cover closed. Eleven test temperatures, from 1000 to 2000 F in 100 F increments, were used for each size of each aggregate in the two conditions of drying.

The selection of the mean test temperature was based on BuAer and BuDocks design requirements. Enclosure (1) of BuAer 11012 of September 1957 stated that blast-resistant pavements shall be designed to withstand a temperature of 1500 F, and NavDocks Specification S-P16 (drawing No. 900464) of April 1960 stated that blast deflectors were designed for a maximum temperature of 1500 F. However, changes in aircraft design and operation in the future may require pavements and blast deflectors to withstand temperatures higher than 1500 F. Therefore, test temperatures above 1500 F to a maximum of 2000 F were included in the investigation. No minimum temperature is specified in the NavDocks Specification, and the test temperatures below 1500 F were arbitrarily selected.

Cooling and Resieving

After three minutes of heating, the sample was immediately removed from the furnace chamber and placed in a can to be cooled to ambient temperature in a ventilated cabinet. The sample was resieved for three minutes using the same sieve which retained the aggregate size when segregated (e.g., 1/2-inch sieve for 1/2-inch sample). The sample retained on the sieve was weighed and subtracted from the original oven-dry weight of the sample to determine the amount of breakdown.

TEST RESULTS

Tables II through VI in Appendix B show the percentages of aggregate breakdown under thermal shock. An analysis of the test results was conducted by the Corporation of Economics, Industry and Research, a firm under contract to NCEL for statistical studies and data analyses. The details of the analysis and results based on the analysis are given in the CEIR report which is in Appendix C. A summary of the findings of that study is given below.

The order of the performance of the five aggregates based on the breakdown of the 1/2-inch aggregate at 1500 F was Virginia diabase, blast-furnace slag, San Gabriel gravel, Santa Clara gravel and Haydite, with the first of these rated best. There was little difference between the breakdown of Virginia diabase and that of the blast-furnace slag. However, the San Gabriel and Santa Clara gravels had twice as much and Haydite had three times as much breakdown as Virginia diabase or blast-furnace slag.

In every case, the breakdown increased with increase in size of aggregate, test temperature, and combination of high temperatures and larger sizes. The increase in breakdown due to size was usually nonlinear. There was also a significant quadratic temperature effect on breakdown in most cases.

Based on the breakdown of the 1/2-inch aggregates at 1500 F, the saturated-surface-dried aggregates had higher breakdown than the oven-dried ones.

DISCUSSION OF TEST RESULTS

During heating of the Santa Clara and San Gabriel gravels, especially the saturated-surface-dry samples, popping of the rocks was heard. The frequency of the popping seemed to increase with increase in temperature. Observations of the cooled samples of these gravels showed that some aggregates were discolored, chipped, fractured and separated into smaller pieces. The types of rocks which appeared to be damaged were granites with bands of mica and ferrous grains, oil shales, cherts, sandstones and flat mudstones. When subjected to the higher test temperatures (above 1500 F), the granites with bands of mica and ferrous grains crumbled into fines when squeezed between the fingers. The fine-grained granites which were free of mica and iron crystals appeared to be most resistant to thermal shock.

The Virginia diabase, blast-furnace slag and Haydite also popped during heating but not as frequently as the river gravels. The blast-furnace slag produced a pungent odor like that of sulphur dioxide. Observation of the cooled diabase, slag and Haydite samples showed that some of the aggregates were chipped and separated into smaller pieces like those of the river gravels; however, no appreciable discoloration of these samples was observed.

FINDINGS AND CONCLUSIONS

1. When loose samples of various types and sizes of aggregates were subjected to various levels of thermal shock in a furnace from 1000 to 2000 F, the larger sizes experienced more breakdown than the smaller ones. Therefore, it appears that the size of aggregate is a contributing factor to spalling of concrete pavement surfaces subjected to thermal shock and that smaller sizes of aggregates are preferable to larger aggregates in heat-resistant concrete.
2. Some types of river rocks such as oil shales, cherts, flat mudstones, and sandstones and granites with mica or ferrous grains were damaged more than granites with fine, homogeneous grain. Therefore, it appears that oil shales, cherts, etc., are not desirable for use in heat-resistant concrete.
3. Saturated-surface-dried aggregates had more breakdown than the oven-dried ones. On the basis of this result and the result of the effect of curing time on the compressive strength of cement-paste cubes determined in another study (see Appendix A), it appears preferable to have the aggregates and cement paste as dry as possible before the concrete is subjected to high thermal shock conditions.

RECOMMENDATION

Since separate studies, one on concrete aggregates and one on cement paste, were conducted, it is recommended that an investigation based on the two studies be made to determine what combination of factors would form a suitable jet-blast-resistant concrete.

Appendix A

SUMMARY OF TR-169, "EFFECT OF TEMPERATURE RISE ON COMPRESSIVE STRENGTH OF HARDENED CEMENT PASTE"

The objective of this task is to determine if the rate of heating cement paste of a concrete mix is a contributing factor to the explosive spalling that takes place when concrete pavement surfaces are subjected to thermal shock.

The compressive strength of heated cement-paste cubes made from Types I, II and III portland cement and two brands of calcium aluminate cement were determined in this study. Two-inch cubes were cured for 8, 29 and 57 days, heated in a gas-fired furnace to elevated temperatures ranging from 1000 to 1800 F at four rates of heating (8, 10, 12 and 14 F per second), and tested in compression after cooling.

All cubes experienced cracking and some experienced damages when heated to high temperatures. Heating decreased the compressive strength of cement-paste cubes. The higher heating rates produced no appreciable effect on the level of compressive strength or in the rate of decrease in strength with increase in maximum temperature. In general, the heated calcium aluminate cement cubes yielded a lower compressive strength than the heated portland cement cubes. The increase in curing from 8 to 29 days produced no significant effect on the compressive strength of the heated cubes, but the 57-day curing resulted in a lower rate of decrease in compressive strength with increase in maximum temperature. By statistical analysis, it was found that a straight line adequately represented the relationship between compressive strength and maximum temperature for each cement, curing time, and heating rate.

On the basis of this study, it appears that rate of heating cement paste is not a contributing factor to spalling of concrete pavement surfaces subjected to thermal shock.

Appendix B
PERCENTAGES OF AGGREGATE BREAKDOWN UNDER THERMAL SHOCK
(Tables II - VI)

Table II. Percent Breakdown of Santa Clara Gravel Under Thermal Shock

Test Temp (F)	Saturated-Surface-Dry					Oven-Dry				
	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4
1000	14.05	13.51	6.31	6.61	2.19	0.76	7.27	2.53	3.28	1.29
	10.91	5.84	6.45	5.42	2.39	1.36	5.02	2.66	3.06	1.59
	12.62	9.11	7.50	5.41	1.99	4.01	6.62	3.19	0.86	1.49
1100	10.96	13.95	9.11	7.13	3.69	4.29	5.80	1.60	3.78	1.69
	11.57	8.65	8.44	6.84	2.69	5.82	3.51	5.32	4.71	2.49
	19.05	10.44	8.77	6.27	2.19	2.97	5.84	3.59	1.78	-
1200	17.97	8.68	10.50	8.76	3.49	2.39	3.59	4.46	3.85	3.34
	12.67	13.00	10.97	8.13	2.89	3.95	10.68	1.79	2.57	3.34
	26.87	13.13	9.31	7.97	3.39	0.59	12.41	3.13	2.98	3.09
1300	13.02	14.83	13.30	7.61	5.37	2.98	13.34	5.38	3.64	4.29
	12.28	13.41	12.36	8.11	4.19	6.64	12.06	2.73	5.65	4.39
	24.32	14.63	10.04	8.34	5.50	2.99	10.12	2.13	4.19	3.88
1400	32.23	11.21	12.85	15.10	7.57	2.41	10.96	5.92	5.13	5.19
	12.63	12.28	18.70	11.38	6.87	3.96	18.11	4.33	4.69	4.79
	11.75	17.67	14.42	9.83	7.37	4.67	12.93	4.33	5.56	6.69
1500	33.45	16.50	17.75	15.23	10.47	6.15	13.89	6.98	7.91	8.16
	20.94	17.47	19.10	14.52	9.58	9.04	20.39	5.93	5.13	5.17
	26.71	19.47	12.18	15.42	9.66	7.34	17.07	5.45	8.83	6.68
1600	18.83	24.11	20.45	18.11	13.27	10.45	17.73	6.98	-	9.75
	22.39	25.86	21.05	17.39	11.35	8.96	17.01	9.93	9.47	10.87
	25.87	21.56	23.99	25.56	11.17	10.89	18.13	11.96	11.46	9.87
1700	31.95	26.59	24.58	23.43	15.70	11.97	18.44	10.00	15.50	13.75
	29.81	21.58	26.92	22.86	16.88	10.64	23.53	12.96	13.04	11.45
	27.69	23.60	26.62	22.25	13.10	14.32	17.27	11.05	14.24	13.28
1800	28.58	27.56	36.70	24.85	19.66	20.38	27.39	14.35	19.41	17.16
	40.25	29.34	38.00	28.77	19.88	18.77	25.35	14.65	13.80	13.85
	32.08	31.15	27.90	28.49	18.08	24.05	19.53	16.55	18.51	17.23
1900	48.90	33.61	38.15	27.19	24.65	30.65	28.22	22.90	19.14	18.68
	46.70	28.28	39.40	32.24	23.13	28.90	25.80	20.00	19.11	22.07
	42.30	33.09	30.60	34.61	25.09	32.30	28.07	22.30	17.80	20.63
2000	52.60	36.20	43.80	43.06	26.97	35.61	42.91	19.71	26.93	26.19
	38.75	30.88	49.30	41.46	27.64	35.40	35.90	20.20	33.28	21.67
	45.60	38.50	41.70	40.55	27.07	28.60	31.21	23.80	29.11	25.02

Table III. Percent Breakdown of San Gabriel Gravel Under Thermal Shock

Test Temp (F)	Saturated-Surface-Dry					Oven-Dry				
	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4
1000	3.25	7.15	5.32	2.39	2.45	2.70	11.85	1.46	0.70	2.46
	1.46	6.17	2.53	2.88	3.22	2.98	4.28	1.60	0.40	2.30
	1.55	10.19	1.20	0.90	2.61	0.83	8.28	2.93	2.09	2.46
1100	1.44	8.16	1.79	2.39	3.53	2.50	3.87	1.99	2.97	3.99
	3.63	7.34	2.86	3.00	5.38	2.27	4.74	2.59	3.88	3.06
	0.96	3.87	2.06	4.09	3.07	1.43	7.53	3.20	1.10	9.87
1200	0.40	9.11	5.73	5.26	1.53	2.65	6.39	3.53	2.69	4.76
	5.32	11.76	5.45	2.59	5.84	4.41	5.63	2.52	2.39	2.15
	0.71	10.89	3.13	3.29	3.23	2.86	12.22	4.06	0.90	5.22
1300	0.84	13.02	6.65	6.36	4.15	3.56	7.98	4.98	5.97	4.92
	5.12	11.06	6.25	6.87	6.00	4.67	11.41	5.52	3.97	5.22
	2.34	6.38	4.00	4.68	5.68	2.50	6.69	5.73	2.69	4.15
1400	1.95	8.44	8.80	9.27	6.30	9.31	9.32	12.96	9.82	8.61
	1.91	16.65	11.60	8.36	6.46	0.55	11.71	5.73	7.96	8.29
	7.97	11.82	7.66	4.29	6.60	7.40	17.77	7.13	5.27	6.61
1500	8.88	10.88	10.65	11.84	8.92	12.43	14.71	9.50	11.14	7.38
	8.88	16.56	13.01	10.80	10.30	10.53	9.96	16.64	5.98	8.29
	9.90	24.41	11.65	10.16	11.67	8.22	11.43	13.49	6.56	10.92
1600	11.69	21.94	19.03	17.95	10.46	9.00	30.88	15.67	9.13	9.84
	22.15	16.08	19.20	18.47	11.07	15.78	29.41	15.97	11.71	10.30
	23.11	13.83	16.14	12.68	9.53	19.40	14.39	17.14	10.41	9.69
1700	12.17	30.16	18.12	15.72	13.53	19.77	27.01	20.48	18.82	10.76
	29.37	35.23	20.81	15.84	14.00	34.10	38.00	16.51	14.85	10.13
	23.48	28.86	23.20	10.64	14.30	20.68	31.70	19.28	16.53	10.44
1800	23.08	44.54	23.42	19.00	14.15	33.65	34.19	23.70	14.22	18.15
	36.36	40.90	23.92	21.03	16.05	37.58	38.87	22.09	19.80	17.38
	49.14	24.69	25.47	15.96	14.15	42.65	39.61	21.53	14.68	16.12
1900	29.25	49.80	25.20	27.21	22.76	33.59	49.03	28.45	26.30	19.53
	39.98	46.59	34.20	25.92	20.30	62.50	56.76	30.49	25.17	18.76
	53.16	36.97	36.91	25.90	21.53	52.64	35.67	27.13	20.67	16.15
2000	37.14	59.63	29.25	28.07	25.38	48.24	66.76	44.87	26.42	23.65
	64.75	61.74	41.71	31.50	24.92	74.40	67.11	34.13	35.92	32.10
	71.92	46.21	40.11	27.97	24.15	72.21	52.48	42.44	33.33	27.23

Table IV. Percent Breakdown of Virginia Diabase Under Thermal Shock

Test Temp (F)	Saturated-Surface-Dry					Oven-Dry				
	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4
1000	0.59	7.08	0.40	7.57	0.60	5.83	6.02	0.50	9.59	0.80
	2.66	5.53	1.74	13.42	0.40	3.89	7.27	0.65	11.99	0.81
	3.31	9.73	0.65	14.34	0.50	2.59	6.02	0.65	12.62	0.71
1100	1.96	5.84	0.95	10.30	1.21	3.56	4.88	1.00	11.91	0.71
	3.92	5.34	1.05	11.21	0.81	0.55	0.50	1.35	13.83	0.50
	7.75	4.97	0.80	10.10	0.80	5.69	3.98	0.75	11.81	0.70
1200	1.95	6.94	1.20	16.64	0.81	4.91	7.85	0.70	16.64	1.21
	2.95	6.28	0.75	14.83	0.81	4.73	2.40	0.95	13.83	1.01
	1.56	8.16	0.80	12.00	0.71	0.43	4.58	1.40	12.32	0.90
1300	2.11	8.73	1.10	14.54	1.31	5.80	1.40	0.85	14.02	1.10
	1.03	7.38	0.75	12.32	1.41	5.33	4.25	0.80	9.39	1.21
	2.73	6.37	1.15	18.76	1.01	0.65	3.64	0.70	15.64	0.91
1400	5.81	9.77	1.45	14.54	1.31	3.75	3.14	2.14	13.94	1.91
	5.27	9.77	1.09	16.35	1.81	2.08	4.49	1.70	15.45	1.81
	3.77	9.18	0.90	16.36	1.62	2.01	5.53	1.39	15.15	1.71
1500	7.68	6.73	2.00	16.06	1.61	10.61	5.28	1.50	14.14	2.01
	11.90	5.88	1.40	14.83	2.11	7.83	5.99	1.44	13.12	1.61
	7.67	7.57	1.59	14.33	2.01	2.72	2.55	2.19	16.16	1.82
1600	11.43	7.65	2.14	15.25	2.22	9.25	5.48	2.14	14.04	2.32
	18.60	6.79	2.34	14.85	2.21	12.19	9.12	1.75	17.68	1.81
	11.38	5.40	2.74	17.36	2.02	7.21	4.33	2.59	15.96	2.01
1700	13.64	6.72	2.94	17.68	2.72	17.02	7.09	2.64	14.14	1.81
	16.92	9.45	2.39	17.78	2.12	21.90	8.61	2.49	15.14	2.42
	7.50	7.17	3.20	16.57	2.31	12.73	11.41	3.24	13.74	2.12
1800	23.72	4.38	4.19	19.19	2.51	28.52	9.70	4.04	17.27	2.62
	22.07	9.89	2.89	15.25	2.71	47.11	7.92	4.19	12.73	2.82
	13.76	10.11	3.54	16.16	2.82	21.47	10.11	2.95	15.24	3.21
1900	22.56	12.95	3.44	18.28	2.62	17.48	11.36	3.08	15.66	3.22
	24.00	11.05	5.77	18.18	2.82	47.35	11.90	3.13	17.17	3.11
	26.05	6.98	3.98	19.80	3.42	12.66	11.41	4.58	16.35	3.30
2000	40.81	14.95	4.23	19.49	3.11	23.51	13.88	4.27	17.68	3.31
	45.65	12.72	6.12	21.52	3.02	48.25	22.63	4.57	20.20	4.45
	21.47	11.61	5.14	17.58	3.11	27.19	13.28	6.73	17.78	3.11

Table V. Percent Breakdown of Blast-Furnace Slag Under Thermal Shock

Test Temp (F)	Saturated-Surface-Dry					Oven-Dry				
	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4
1000	2.00	3.74	5.29	16.75	5.36	1.15	3.40	3.14	6.45	1.79
	0.93	6.67	5.64	16.35	5.73	1.31	3.20	2.64	4.38	1.68
	1.31	2.60	6.36	11.88	5.67	1.16	4.94	5.93	9.15	1.78
1100	1.77	4.67	3.35	12.21	6.08	1.15	4.39	4.15	10.55	1.79
	3.38	5.00	11.43	15.20	5.55	3.08	3.27	5.64	9.56	1.70
	2.62	4.00	6.50	15.71	7.06	1.15	2.74	3.93	10.81	1.49
1200	3.07	6.67	6.64	14.29	6.27	1.62	1.06	3.78	8.06	1.89
	4.70	3.46	6.86	16.98	7.67	0.92	4.60	3.93	6.94	1.49
	3.31	5.74	7.93	16.99	6.96	1.54	2.33	3.22	7.10	1.99
1300	6.48	7.67	4.14	15.91	7.86	11.00	6.67	3.36	11.64	2.68
	4.22	4.92	6.86	18.29	6.97	5.86	3.06	1.86	9.88	3.08
	17.94	7.72	7.14	20.10	7.16	7.47	7.08	3.42	6.70	1.89
1400	18.40	9.27	10.29	19.25	7.27	12.24	2.67	5.14	7.02	2.59
	20.06	7.47	8.29	15.20	8.37	5.99	6.20	4.29	9.09	2.28
	11.65	8.65	7.93	16.31	8.06	7.09	4.00	4.71	12.81	2.79
1500	22.26	7.71	6.72	15.95	8.83	10.42	7.81	4.29	11.12	2.89
	15.77	6.26	5.58	16.95	8.34	16.10	6.27	3.43	8.05	3.59
	17.11	7.72	5.65	15.09	8.06	8.46	2.20	4.64	13.09	2.98
1600	40.77	14.16	11.58	15.48	9.12	21.93	5.26	7.80	8.69	4.07
	37.34	11.88	7.57	10.10	9.23	6.17	6.94	7.29	8.78	3.58
	19.89	8.60	6.58	16.79	10.23	12.35	2.47	6.13	7.65	3.38
1700	29.79	13.99	7.57	15.28	10.15	24.75	11.34	4.07	7.67	3.68
	32.64	7.31	10.29	18.95	9.96	21.90	8.06	4.80	8.33	3.79
	40.09	7.74	7.64	17.60	9.76	32.56	7.78	6.37	6.71	4.07
1800	41.80	18.28	12.19	16.71	10.72	33.82	6.21	6.65	9.16	3.58
	33.30	15.68	8.57	18.25	11.05	24.90	10.33	7.57	7.01	4.27
	27.64	14.61	10.86	18.98	10.71	23.86	13.13	4.71	7.10	3.59
1900	42.08	23.76	8.99	15.54	11.86	20.41	17.36	7.50	8.53	4.07
	55.21	17.23	9.06	16.79	11.24	29.29	17.33	7.57	7.97	4.06
	37.75	25.05	9.36	14.81	10.92	41.47	19.22	7.85	8.09	4.48
2000	47.62	28.28	9.64	16.89	11.72	39.71	18.53	8.21	5.98	4.07
	48.03	29.31	9.14	16.88	11.61	45.66	20.47	7.28	6.94	4.17
	54.62	28.34	7.14	19.25	12.04	29.13	15.82	7.08	8.54	3.98

Table VI. Percent Breakdown of Haydite Under Thermal Shock

Test Temp (F)	Saturated-Surface-Dry					Oven-Dry				
	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4
1000	22.49	11.02	4.40	12.13	2.50	23.71	10.82	8.58	7.24	1.50
	33.79	14.36	6.15	12.37	3.00	23.10	16.31	9.96	7.66	2.49
	30.39	8.13	10.38	9.52	3.00	32.33	9.62	6.11	4.65	3.50
1100	36.08	10.64	9.88	9.65	3.25	26.81	7.48	5.72	6.82	2.98
	38.09	11.82	8.13	9.48	3.75	34.30	8.96	9.27	6.01	2.50
	49.20	13.86	7.00	14.83	2.75	32.46	7.76	8.88	8.16	2.00
1200	31.25	12.89	8.81	12.00	4.23	35.05	5.54	12.11	11.02	3.48
	36.80	11.46	8.82	9.80	5.00	31.52	14.71	7.14	9.32	4.01
	44.49	14.74	10.68	9.50	5.25	37.70	12.16	5.88	8.94	3.25
1300	39.45	12.89	11.75	8.50	3.75	34.21	10.46	5.85	4.65	2.99
	53.04	18.48	16.14	6.67	2.51	34.17	12.98	9.44	5.00	3.48
	49.18	17.75	8.60	8.79	3.50	40.27	11.28	8.99	7.50	4.26
1400	41.05	9.76	12.29	13.31	5.48	53.69	9.71	7.43	6.52	3.50
	55.46	23.00	8.14	9.95	3.50	41.78	11.73	10.46	4.65	3.25
	62.40	22.93	10.11	11.83	3.25	68.56	16.11	7.43	6.32	2.75
1500	53.15	29.83	-	12.47	3.25	46.75	23.65	13.73	10.00	4.25
	58.15	29.04	16.11	10.53	3.75	50.41	22.83	9.96	5.99	3.75
	60.63	33.37	12.71	9.34	3.00	53.11	17.12	11.72	8.50	3.25
1600	67.76	47.62	20.71	13.64	3.50	-	34.10	16.18	9.33	2.25
	61.08	46.56	23.82	16.08	2.50	66.76	38.68	17.31	11.00	2.75
	77.27	53.34	24.54	13.10	3.75	72.47	45.35	13.98	12.68	2.75
1700	73.87	49.44	31.71	27.71	2.25	66.70	41.98	22.30	12.67	2.50
	84.23	44.38	27.03	19.66	2.75	77.72	53.65	17.84	15.32	3.25
	88.68	72.48	27.18	15.35	2.25	75.23	51.16	22.65	13.35	2.25
1800	78.86	69.47	47.42	16.52	3.00	72.55	52.03	30.62	9.64	2.50
	85.96	58.71	46.21	19.69	4.00	82.64	66.40	30.18	10.17	2.50
	86.82	76.26	43.46	19.19	3.50	82.84	65.27	27.18	14.35	3.00
1900	82.88	67.33	45.22	17.97	3.00	74.09	64.93	33.00	11.83	2.00
	88.90	65.81	48.64	16.25	3.50	76.91	51.64	25.96	10.18	1.75
	85.64	74.72	40.79	17.63	2.75	76.42	56.93	38.92	9.20	1.25
2000	92.03	73.50	-	15.18	2.75	79.28	66.18	19.42	6.67	2.25
	85.09	70.39	31.33	13.48	3.50	82.31	76.79	18.11	6.34	1.50
	85.50	73.98	37.05	15.16	2.75	81.28	72.12	27.38	9.19	2.00

Appendix C
DATA ANALYSIS FOR "AGGREGATE SIZE VS HEATING STUDIES"

Task Y-F015-15-106

by

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SUMMARY

Data analyses were made for an experiment that had been conducted to determine if the heating of aggregates used in concrete causes breakdown of the aggregate. By means of a statistical model it was found for each of five kinds of aggregate, dried in two different manners, that the larger size of aggregate, the higher temperatures, and their interaction resulted in significantly higher breakdown. In order to characterize the pertinent parameters contributing to the above results, a mathematical model of this process was developed. While several of these parameters were computed, it appears that the additional effort required to compute all of them is not warranted at this time.

INTRODUCTION

"The objective of this study is to determine if the size of the aggregate used in the concrete mix is a contributing factor to the explosive spalling that takes place when concrete pavement surfaces are subjected to thermal shock."

In this investigation there were five types of aggregates, five sizes of each aggregate, two methods of drying, eleven temperatures, and three samples for each combination of these, making a total of 1650 tests in all. As a result of each test a measure of breakdown was obtained.

The following statistical model relates the measure of breakdown to the applied treatments. A separate evaluation was done for both of the two methods of drying and for each of the five aggregates, making a total of ten separate evaluations.

DEFINITION OF TERMS

z = size of aggregate minus 1/2 inch

t = (temperature minus 1500 F) divided by 1000

i = sample designation (1, 2, or 3)

$y_{z,t,i}$ = the measure of the breakdown for aggregate size z , for temperature t , and for sample i

$b_1, b_2, b_3, b_4, b_5, b_6$ = the regression coefficients to be estimated

$e_{z,t,i}$ = the deviation of the observed $y_{z,t,i}$ from the value obtained by using the statistical model

STATISTICAL MODEL

In the following model it is proposed that the underlying relationship between the size and temperature factors and the breakdown can be well represented by a three-dimensional quadratic response surface. It may be assumed that individual trials can deviate from this underlying relationship in a random manner, and that this deviation is $e_{z,t,i}$. These may further be assumed to be normally distributed with a mean value of zero and with some variance estimated as s^2 .

$$y_{z,t,i} = b_1 + b_2 z + b_3 t + b_4 z^2 + b_5 zt + b_6 t^2 + e_{z,t,i}$$

It may be noted that when the average size of aggregate is used, z would be zero; and when the average temperature is used, t would be zero, so that most of the terms on the right side of the above equation would vanish, leaving only b_1 and the error term. Thus b_1 is an estimate of the breakdown under "average conditions" and would be a basis for comparing the different aggregates and methods of drying. The quantities b_2 and b_3 are the estimates of the linear effects of size and temperature respectively on the breakdown. The quantities b_4 and b_6 are the corresponding quadratic effects, and b_5 is the interaction effect.

It is the purpose of this data analysis to estimate these effects from the data.

EQUATIONS

There is an equation corresponding to each combination of z , t , and i . These can be written in a list:

$$y_{-\frac{5}{16}, -\frac{1}{2}, 1} = b_1 - \frac{5}{16} b_2 - \frac{1}{2} b_3 + \frac{25}{256} b_4 + \frac{5}{32} b_5 + \frac{1}{4} b_6 + e_{-\frac{5}{16}, -\frac{1}{2}, 1}$$

$$y_{-\frac{5}{16}, -\frac{1}{2}, 2} = b_1 - \frac{5}{16} b_2 - \frac{1}{2} b_3 + \frac{25}{256} b_4 + \frac{5}{32} b_5 + \frac{1}{4} b_6 + e_{-\frac{5}{16}, -\frac{1}{2}, 2}$$

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$$y_{\frac{1}{2}, \frac{1}{2}, 3} = b_1 + \frac{1}{2} b_2 + \frac{1}{2} b_3 + \frac{1}{4} b_4 + \frac{1}{4} b_5 + \frac{1}{4} b_6 + e_{\frac{1}{2}, \frac{1}{2}, 3}$$

It is convenient to redefine subscripts and symbols for these equations, making them:

$$\begin{aligned}
 y_1 &= x_{1,1} b_1 + x_{1,2} b_2 + x_{1,3} b_3 + x_{1,4} b_4 + x_{1,5} b_5 + x_{1,6} b_6 + e_1 \\
 y_2 &= x_{2,1} b_1 + x_{2,2} b_2 + x_{2,3} b_3 + x_{2,4} b_4 + x_{2,5} b_5 + x_{2,6} b_6 + e_2 \\
 &\vdots \\
 y_{165} &= x_{165,1} b_1 + x_{165,2} b_2 + x_{165,3} b_3 + x_{165,4} b_4 + x_{165,5} b_5 \\
 &\quad + x_{165,6} b_6 + e_{165}
 \end{aligned}$$

It may be noted that $x_{1,1} = x_{2,1} = \dots = x_{165,1} = 1$.

The above list of equations may be expressed as:

$$y_i = \sum_{j=1}^6 x_{ij} b_j + e_i$$

In matrix form, this is:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{165} \end{bmatrix} = \begin{bmatrix} x_{1,1} & x_{1,2} & \dots & x_{1,6} \\ x_{2,1} & x_{2,2} & \dots & x_{2,6} \\ \vdots & \vdots & \dots & \vdots \\ x_{165,1} & x_{165,2} & \dots & x_{165,6} \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_{165} \end{bmatrix}$$

This may be represented in matrix notation as:

$$Y = X B + E$$

METHOD OF SOLUTION

The least squares estimate of the b's is:

$$B = (X'X)^{-1} X'Y$$

The steps in the solution are:

1. Obtain $(X'X)$, $(X'Y)$ and $(Y'Y)$.

Note that any element of $X'X$, say p_{ij} , is the summary product:

$$p_{ij} = \sum_{k=1}^{165} x_{ki} x_{kj}$$

Any element of $X'Y$ is of the form:

$$q_i = \sum_{k=1}^{165} x_{ki} y_k$$

The quantity $Y'Y$:

$$Y'Y = \sum_{k=1}^{165} y_k y_k = \sum_{k=1}^{165} y_k^2$$

2. Invert the matrix $X'X$ to get $(X'X)^{-1}$.

Note that both $X'X$ and $(X'X)^{-1}$ are symmetric matrices.

3. Obtain B by the matrix product of $(X'X)^{-1}$ and $(X'Y)$.

Note that if an element of the matrix $(X'X)^{-1}$ is designated as r_{ij} , where i is the row number and j is the column number, then an element of the vector B , say b_i is the summary product:

$$b_i = \sum_{j=1}^6 r_{ij} q_j$$

4. The variance associated with $e_{z, t, i}$ is estimated by:

$$s^2 = \frac{1}{165 - 6} \left[Y'Y - B'(X'Y) \right] = \frac{1}{159} \left[\sum_{k=1}^{165} y_k^2 - \sum_{i=1}^6 b_i q_i \right]$$

Since there were 165 observations and six coefficients estimated, the number of degrees of freedom associated with this s^2 is $165 - 6 = 159$. $Y'Y$ is the total sum of squares, and $B'(X'Y)$ is the reduction in this total due to fitting the model to these observations.

5. Obtain the variance covariance matrix by multiplying each element of the $(X'X)^{-1}$ matrix by s^2 . If an element of the variance covariance matrix is designated as σ_{ij} , then:

$$\sigma_{ij} = s^2 r_{ij}$$

As a result, the variance associated with b_1 is $\sigma_{1,1}$, with b_2 is $\sigma_{2,2}$, and with b_i is σ_{ii} . The covariance associated with two of the b 's, say b_i and b_j , is σ_{ij} .

6. A 95-percent confidence interval can be associated with each of the b 's, say b_i , by taking $b_i \pm 1.96 \sqrt{\sigma_{ii}}$.

RESULTS OF DATA ANALYSIS

The results of this analysis are shown in Table C-1. For each of the five types of aggregate, and for each of the methods of drying indicated by (SSD) and (OD), the values of the b 's are given in units of percent breakdown. Immediately below each b are the associated 95-percent confidence limits. The b 's which are not significantly different from zero are in brackets. It may be noted that the corresponding confidence interval for these include zero. As a rule of thumb, any two of these b 's which are compared are significantly different if their confidence intervals do not overlap.

The five aggregates are listed in order of their over-all performance. Virginia diabase and slag had the smallest over-all breakdown. Santa Clara and San Gabriel had approximately twice as much breakdown, while Haydite had approximately three times as much breakdown.

The (SSD) method of drying resulted in a higher over-all breakdown than the (OD) method, as indicated by the corresponding (b_1) values. Otherwise (SSD) and (OD) were quite consistent with respect to the remaining b 's. The exceptions to this are the linear effects of size (b_2) of the Santa Clara and Haydite aggregates, and the linear effects of temperature (b_3) of the Santa Clara aggregate.

Table C-1. Summary of Effects of Size and Temperature for Five Aggregates Dried in Two Ways
(and Associated 95% Confidence Limits)

Aggregate	Average (Over-all)	Size (Linear)	Temperature (Linear)	Size (Quadratic)	Size-Temp (Interaction)	Temperature (Quadratic)
	(b ₁)	(b ₂)	(b ₃)	(b ₄)	(b ₅)	(b ₆)
Va. Diabase (SSD)	6.57 (4.8,8.3)	8.01 (3.8,12.3)	8.08 (5.1,11.1)	[-3.02] (-16.6,10.5)	27.81 (17.5,38.1)	11.38 (.8,21.9)
(OD)	5.42 (3.6,7.2)	7.54 (3.0,12.1)	8.84 (5.6,12.0)	[4.34] (-10.1,18.7)	33.67 (22.7,44.6)	15.15 (3.9,26.3)
Slog (SSD)	9.38 (7.8,11.0)	6.56 (2.7,10.5)	13.27 (10.5,16.0)	31.09 (18.7,43.5)	58.34 (48.9,67.8)	[9.13] (-5,18.8)
(OD)	5.18 (4.0,6.3)	9.81 (7.0,12.6)	8.93 (6.9,10.9)	13.86 (4.9,22.8)	44.86 (38.0,51.7)	9.77 (2.8,16.7)
San Gabriel (SSD)	12.63 (11.1,14.1)	16.64 (13.0,20.3)	34.27 (31.7,36.9)	-23.89 (-35.5,-12.2)	41.75 (32.9,50.6)	42.26 (33.2,51.3)
(OD)	11.06 (9.5,12.6)	18.29 (14.5,22.0)	36.27 (33.6,38.9)	-16.19 (-28.1,-4.3)	51.39 (42.3,60.5)	52.06 (42.8,61.3)
Santa Clara (SSD)	16.76 (15.6,17.9)	17.47 (14.7,20.2)	31.16 (29.2,33.1)	-12.99 (-21.8,-4.2)	[3.15] (-3.6,9.9)	26.56 (19.7,33.4)
(OD)	9.35 (8.4,10.3)	7.84 (5.4,10.2)	24.42 (22.7,26.1)	-11.78 (-19.4,-4.2)	11.06 (5.2,16.9)	29.17 (23.3,35.1)
Haydite (SSD)	19.94 (17.9,22.0)	64.69 (59.7,69.7)	31.24 (27.7,34.8)	29.73 (13.8,45.7)	92.65 (80.6,104.7)	[10.61] (-1.9,23.1)
(OD)	14.02 (12.0,16.1)	53.96 (49.0,59.0)	25.39 (21.8,28.9)	51.94 (35.9,68.0)	92.59 (80.4,104.7)	[10.95] (-1.5,23.4)

In every case there was a strong effect (b_2) due to size of aggregate. The larger the size of aggregate, the greater the breakdown. Since in most cases, the quadratic effect (b_4) of size was either significantly more or less than zero, it can be concluded that the size effect is nonlinear.

In every case there was a strong effect (b_3) due to the temperature to which the aggregate was heated; the higher the temperature, the greater the breakdown. Since, in most cases, the quadratic effect (b_6) of temperature was significantly greater than zero it can be concluded that the breakdown is much more severe at the higher temperatures.

Since, in most cases, the size-temperature interaction (b_5) is significantly positive, it may be concluded that the breakdown of the larger size of aggregate at the higher temperatures is even more severe than what might be expected on the basis of the simple size and temperature effects.

The only aberration noted in the data was that the breakdown of the 3/8-inch Virginia diabase was not consistent with the breakdown observed for the other sizes of this aggregate.

ESTIMATION OF PARAMETERS

Mathematical Model

In order to estimate the parameters associated with the breakdown of the aggregate, a mathematical model was developed. For a particular kind and size of aggregate and method of drying, the three parameters to be estimated are:

- B - where $(1 - B)$ is the proportion of aggregate which would seem to break down even if there were no heating or thermal stress. Ordinarily B should be near, but not exceed, 1.00.
- S - the temperature at which all of the aggregate would break down.
- R - the rate at which the tendency of the aggregate to break down increases as the temperature increases.

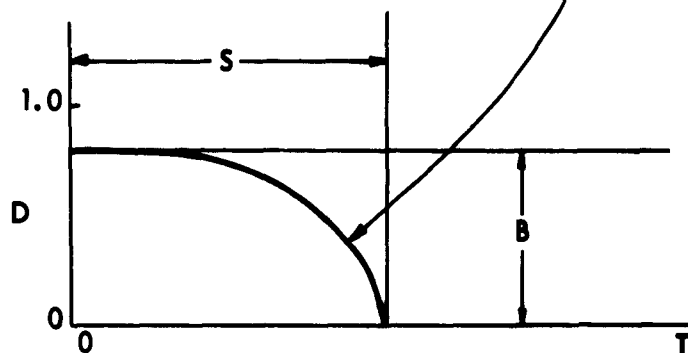
The other factors which enter into this model are:

- T - temperature to which the aggregate was heated.
- D - proportion of aggregate not broken down at temperature T.

The mathematical model relating these quantities is:

$$D = B \left[1 - e^{-R(S-T)} \right]$$

A sketch of this model and related data is:



The model for this data is approximated in the vicinity of R by using an estimate R_0 of R :

$$D \approx B - CX - ETX$$

where $C = b e^{-R_0 S}$

$$X = e^{R_0 T}$$

$$E = C(R - R_0)$$

The data to be fitted by the model is in the form:

i	$\frac{D_i}{D_1}$	$\frac{T_i}{1000}$
1	$\frac{D_1}{D_1}$	1000
2	$\frac{D_2}{D_1}$	1100
3	$\frac{D_3}{D_1}$	1200
.	.	.
.	.	.
.	.	.
11	$\frac{D_{11}}{D_1}$	2000

Method of Estimation

1. Select an R_o .
2. Compute $X_i = e^{R_o t_i}$.
3. Compute and solve for B, C, and E:

$$\begin{bmatrix} N & \sum X_i & \sum T_i X_i \\ \sum X_i & \sum X_i^2 & \sum T_i X_i^2 \\ \sum T_i X_i & \sum T_i X_i^2 & \sum T_i^2 X_i^2 \end{bmatrix} \begin{bmatrix} B \\ -C \\ -E \end{bmatrix} = \begin{bmatrix} \sum D_i \\ \sum D_i X_i \\ \sum D_i T_i X_i \end{bmatrix}$$

(N is the number of items of data.)

4. $R = R_o + \frac{E}{C}$.
5. $S = \frac{1}{R} \ln \frac{B}{C}$.
6. Compute (predicted D_i) = $V_i = B - CX_i - ET_i X_i$.
7. Compute variance $s^2 = \frac{1}{N-3} \sum_{i=1}^N (D_i - V_i)^2$.

Example

$$R_o = 0.097561$$

i	T_i	D_i	X_i	$V_i = \text{predicted } D_i$	$D_i - V_i$
1	11	0.5893	2.92463	0.6131	-0.024
2	13	0.5273	3.55477	0.5021	0.025
3	15	0.4260	4.32071	0.3814	0.045
4	17	0.1800	5.25161	0.2519	-0.072
5	19	0.1413	6.38314	0.1155	0.026
					0.000

$$\begin{bmatrix} 5 & 22.4349 & 353.7511 \\ 22.4349 & 108.1826 & 1781.3895 \\ 353.7511 & 1781.3895 & 30050.2387 \end{bmatrix} \begin{bmatrix} B \\ -C \\ -E \end{bmatrix} = \begin{bmatrix} 1.8639 \\ 7.28577 \\ 104.14206 \end{bmatrix}$$

$$B = 1.433946$$

$$-C = 0.382620$$

$$-E = 0.009267$$

$$R = R_o + \frac{E}{C} = 0.097561 - 0.024220 = 0.073341$$

$$s^2 = \frac{1}{5-3} (0.009086) = 0.004543$$

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